

# The remarkable starburst-driven outflow in NGC 2782

Shardha Jogee<sup>1</sup>, Jeffrey D. P. Kenney<sup>1</sup> & Beverly J. Smith<sup>2</sup>

Received \_\_\_\_\_; accepted \_\_\_\_\_

---

<sup>1</sup>Yale University Astronomy Department, New Haven, CT 06520-8101

<sup>2</sup> IPAC/Caltech, Pasadena, CA 91125

## ABSTRACT

We show that the starburst-driven outflow in the peculiar galaxy NGC 2782 forms a well-defined collimated bubble which has an extent of  $\sim 1$  kpc and a closed shell at its edge, as seen in  $H\alpha$ , [O III], and 5 GHz radio continuum. The shell coincides with the maximum in intensity and linewidths of [O III] lines in a blueshifted emission nebula which was previously detected via optical spectroscopy by Boer et al. (1992). Such a remarkable outflow morphology has not been observed to date in any other starburst galaxy of comparable luminosity. The radio continuum map reveals a second bubble of similar size on the opposite side of the nucleus, forming a striking double-bubble outflow morphology. We argue from the morphology and short timescale ( $\sim 4 \times 10^6$  years) of the outflow that it is dynamically younger than freely-expanding outflows seen in other galaxies which harbor circumnuclear starbursts of comparable luminosity, e.g., M82. We suggest that the outflow in NGC 2782 is in the early stage where thermal instabilities have not yet completely ruptured the outflow bubble. We present evidence that the outflow is driving warm and hot ionised gas, and possibly cold molecular gas, out of the central kpc of the galaxy. We estimate the contribution of the hot, warm, and cold phases of the ISM to the energetics of the outflow. This study is based on our optical BVR,  $H\alpha$ , and [O III] observations from the WIYN telescope and OVRO CO interferometric data, along with available 5 GHz radio continuum and ROSAT X-ray maps.

*Subject headings:* galaxies: starburst — galaxies: ISM — galaxies: interactions — ISM: jets and outflows — galaxies: evolution — galaxies: structure

## 1. Introduction

Starburst-driven winds can influence the formation and evolution of galaxies. Such winds can drive metal-enriched material out of the galactic plane, thus affecting the mass-metallicity relation between galaxies, the metallicity-radius relation within galaxies and the enrichment of intracluster medium (e.g, Dekel & Silk 1986; Heckman, Lehnert, & Armus 1993, and references therein). In addition, the properties of young stellar components built by central starbursts depend on the rate at which starburst-driven winds blow the ISM out of the galaxy. It is therefore important to study how starburst-driven winds are triggered and evolve. A starburst-driven outflow can be associated with a large spectrum of emission e.g., radio continuum (RC), optical, UV, and X-rays. The relative intensity and distribution of the emission at different wavelengths give critical clues about the evolutionary phase of the outflow and physical conditions in the ISM. Nuclear outflows have been observed in a large number of starburst and Seyfert galaxies (e.g., M82, NGC 253, NGC 3628, NGC 3079, Arp 220, NGC 6240, NGC 4666, NGC 4945, NGC 1068, NGC 1320, NGC 4235) as discussed by many authors (see Heckman et al. 1993; Baum et al. 1993; Lehnert & Heckman 1995; Colbert et al. 1996; Dahlem et al. 1997, & references therein). In this paper, we describe the starburst-driven outflow in the peculiar galaxy NGC 2782; the outflow has a remarkable morphology that has not been observed to date in any other starburst galaxy of comparable luminosity. This study is based on our optical BVR,  $H\alpha$ , and [O III] images from the WIYN (Wisconsin Indiana Yale NOAO) telescope and  $2''$  resolution OVRO (Owens Valley Radio Observatory) CO ( $J=1\rightarrow 0$ ) data, along with available 5 GHz RC observations (Saikia et al. 1994), and an archival ROSAT X-ray map. In this paper, we focus on the starburst-driven outflow and describe the optical observations in detail. In paper II (Jogee, Kenney & Smith 1997), we describe the observations and full analysis of the CO data, and present evidence for a nuclear bar fuelling molecular gas into the central starburst.

## 2. Previous work on the inner few kpc of NGC 2782

NGC 2782 is a nearby ( $D=34$  Mpc for  $H_0$  of  $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ), peculiar galaxy with a pair of HI and optical tails (Sandage & Bedke 1994; Smith 1991), and three ripples within the disk (Arp 1966; Smith 1994). The HI and optical properties can be modelled with a recent interaction or merger of two disk galaxies of unequal mass (Smith 1994). Previous  $H\alpha$  maps (Hodge & Kennicutt 1983; Smith 1994; Evans et al. 1996) showed an arc of emission along the

inner ripple at  $r \sim 25''$  (4.2 kpc), and an unresolved bright region of star formation in the inner  $10''$  (1.7 kpc) radius. This region harbors one of the most luminous circumnuclear starbursts among nearby ( $D < 40$  Mpc) spirals (Devereux 1989), with a FIR luminosity ( $2 \times 10^{10} L_{\odot}$ ; Smith 1991) comparable to M82. The circumnuclear region has optical emission spectra indicative of HII regions (Sakka et al. 1973; Balzano 1983; Kinney et al. 1984), as well as an additional component of highly excited, highly ionised gas (Kennicutt et al. 1989). Boer, Shultz, and Keel (1992) used spatially resolved spectra to show that the high excitation gas lies in a blueshifted outflowing emission nebula. The 5 GHz RC map at  $1''$  resolution presented by Saikia et al. (1994) revealed an intriguing set of peaks and bubbles, for which no explanation has yet been proposed. The detailed distribution and kinematics of molecular gas in the central region was previously unknown as NGC 2782 had been mapped only with single dish observations (e.g., Young et al. 1995) and low resolution ( $6''$ ) interferometry with the Nobeyama Millimeter Array (Ishizuki 1994). The latter study shows an elongated feature with two barely resolved CO peaks. The higher ( $2''$ ) resolution CO data we present in paper II (Jogee et al. 1997) resolves the elongated feature into a clumpy, double-lobed bar-like feature of radius  $\sim 7.5''$  (1.3 kpc).

### 3. The remarkable outflow morphology revealed by new observations

Two 5 min. exposures of NGC 2782 were taken in  $H\alpha + [N II]$ ,  $[O III]$ , off-line continuum and Harris BVR filters on the 3.5 m WIYN telescope at KPNO in December 1995 and March 1996. A 2048 x 2048 S2KB CCD with a plate scale of  $0.2''/\text{pixel}$  was used, giving a field of view of  $6.8' \times 6.8'$  (69 kpc x 69 kpc). Exposures were taken in on-line and off-line filters centered on  $6618 \text{ \AA}$  and  $6709 \text{ \AA}$  for the redshifted  $H\alpha + [N II]$   $\lambda\lambda 6563 \text{ } 6583 \text{ \AA}$  emission lines, and on  $5055 \text{ \AA}$  and  $5176 \text{ \AA}$  for the redshifted  $[O III]$   $\lambda\lambda 4959 \text{ } 5007 \text{ \AA}$  emission lines. The bandwidths of the four filters were 74, 71, 32, and  $52 \text{ \AA}$  respectively. The average seeing in the images was  $0.8''$  except for the B and  $[O III]$  images where it was  $\sim 1.3''$ . We used the IRAF package to obtain continuum-free  $[O III]$  and  $H\alpha + [N II]$  (thereafter referred to as  $H\alpha$ ) images. The registration accuracy of the optical images is  $\sim 1''$ .

The full field of view WIYN R image (Fig. 1, Plate L1) shows the two stellar tails, the optical disk, and the three ripples at radii of  $25''$ ,  $45''$ , and  $60''$ . Except for these three ripples, the optical disk looks relatively undisturbed within a radius of  $1'$  (10 kpc). A magnified view of the inner disk region, as seen in the B-V image, is shown in Fig. 2a (Plate L2). It reveals two

straight dust lanes which are offset from the nucleus and extend out to the inner ripple. The northern dust lane is redder and more prominent than the southern one. The dust lanes bracket the circumnuclear region of star formation which is shown in  $H\alpha$  in Fig. 2b (Plate L2). This  $H\alpha$  map has a higher resolution ( $0.8''$ ) than previously published maps and resolves the region of star formation into (i) a centrally concentrated  $H\alpha$  peak, (ii) a clumpy, arc-like feature about  $3''$  ( $0.5$  kpc) north of the peak, extending east-west over  $10''$ , and (iii) an  $H\alpha$  bubble with a shell feature  $\sim 6''$  S of the nucleus.

In order to unravel the interplay between the molecular gas, the starburst, and the nuclear outflow, we compare this  $H\alpha$  image with the  $[O\ III]$  image, the CO data presented in Paper II, and the 5 GHz RC maps from Saikia et al. (1994). This striking comparison is shown in Figures 3a-3d (Plate L3). The RC map shows a compact central component which is surrounded by secondary peaks to the east and west, and two extended bubbles to the north and south. The central RC,  $H\alpha$ , and  $[O\ III]$  peaks are coincident within the uncertainties, and lie between the two CO lobes (Fig. 3a). The optical emission lines in the inner  $3''$  radius show narrow line widths (full width half maximum (FWHM)  $\sim 300\text{ km s}^{-1}$ ) and line ratios typical of HII regions (Boer et al. 1992). Thus, the central RC,  $H\alpha$ , and  $[O\ III]$  peaks are likely produced by massive star formation. The secondary eastern and western RC peaks lie within the CO bar (Fig. 3a) in a region which is associated with a large amount of molecular gas, shows strong  $H\alpha$  emission, and has optical line ratios consistent with star formation (Boer et al. 1992). Therefore, the secondary RC peaks are also probably due to massive stars.

However, the northern and southern RC bubbles may have a different origin. They are not associated with much molecular gas (Fig. 3a) and are elongated along the CO kinematic minor axis which has a position angle of  $\sim 165$  deg (Paper II). The northern RC bubble has a more fragmented morphology than the southern one and does not have optical counterparts. The southern RC bubble is associated with the  $H\alpha$  bubble (Fig. 3c) and a bright  $[O\ III]$  bubble (Fig. 3d), and all three bubbles show a shell feature at  $\sim 6''$  ( $1$  kpc) south. At this position, optical spectra (Boer et al. 1992) show that the  $[O\ III]$  lines have a strong extranuclear peak, a large FWHM of  $\sim 580\text{ km s}^{-1}$ , a blueshift of  $120\text{ km s}^{-1}$ , and an  $[O\ III]/H\beta$  ratio of  $\sim 4$ . The  $[O\ III]$  image in Fig. 3d (Plate L3) also shows an extranuclear peak which lies in the shell and has an intensity about half that of the nuclear peak. We thus propose that the southern  $H\alpha$ ,  $[O\ III]$ , and RC bubbles, as well as the northern RC bubble, are part of a starburst-driven outflow

emanating from the nucleus. The absence of an optical counterpart to the northern RC bubble can be explained in terms of extinction by dust in the optical disk of NGC 2782. The relatively undisturbed and circular appearance of the disk (Fig. 1, Plate L1), as well as kinematic evidence presented in Paper II, suggests a low inclination for the disk. Furthermore, the near side of the disk is probably to the north since the dust lanes are redder and more prominent (Mihalas & Binney 1981) in the northern side of the disk (see Fig. 2a, plate L2). We therefore conclude that the northern outflow bubble lies behind the disk and is probably obscured from view at optical wavelengths by dust in the disk.

#### 4. The evolutionary phase of the starburst-driven outflow

The starburst-driven outflow in NGC 2782 has a well-defined collimated bubble morphology with a closed shell at its outer edge, as seen in  $H\alpha$ ,  $[O\ III]$ , and RC. Such an unusual outflow morphology has not been previously observed in any other starburst galaxy of comparable luminosity (see e.g., Heckman et al. 1993; Lehnert & Heckman 1995, & references therein). In most outflows, the  $H\alpha$  and non-thermal RC form complex sets of filaments and loops (e.g., M82, NGC 253, NGC 3628, NGC 4666; see Heckman et al. 1993; Seaquist & Odegard 1991; Bland & Tully 1988; Fabbiano et al. 1992; Dahlem et al. 1997, & references therein). The soft X-ray and RC emission often extends further out than the  $H\alpha$ . The known outflow most similar to NGC 2782 is that in the LINER galaxy NGC 3079. This galaxy has an  $H\alpha$  bubble of radius  $13''$  (1.1 kpc), with a shell feature at its outer edge. However, in contrast to NGC 2782, the RC emission in NGC 3079 forms two highly fragmented halos which extend twice as far as the  $H\alpha$  bubble (Ford et al. 1986; Veilleux et al. 1994).

What accounts for the remarkable outflow morphology in NGC 2782? Theory predicts that in the early stages of a starburst-driven outflow, supernovae and winds from massive stars inject energy into the ISM and produce a bubble of very hot gas and thermalised ejecta (e.g., Chevalier & Clegg 1985; Tomisaka & Ikeuchi 1988; Heckman, Armus, & Miley 1990). The bubble expands, sweeping up ambient gas into a thin, dense, optically-emitting shell. Non-thermal RC can be produced when relativistic plasma which is driven along the pressure gradient of the ISM, undergoes synchrotron losses and inverse Compton scattering (e.g., Heckman et al. 1993; Baum et al. 1993; Colbert et al. 1996). Once the bubble is several times the scale height of the ambient gas (blowout phase), the swept-up shell fragments through thermal instabilities and

allows the hot gas to expand freely. For instance, the starburst galaxy M82 is likely to be in this post-blowout, freely-expanding phase (e.g., Heckman et al. 1990), where the dense shell has ruptured, allowing the RC-emitting plasma and the hot X-ray-emitting gas to escape beyond the optical nebula. On the other hand, NGC 3079 might be in the blowout, partially-ruptured bubble phase (Veilleux et al. 1994). We suggest that the southern starburst-driven outflow in NGC 2782 is dynamically younger than these outflows; it is probably in a pre-blowout or early stages of a blowout phase where thermal instabilities have not yet completely ruptured the optical bubble. The electron densities ( $n_e = 600 \pm 200 \text{ cm}^{-3}$  from the  $[\text{S II}]\lambda 6716 \text{ \AA}/[\text{S II}]\lambda 6730 \text{ \AA}$  line ratio; Boer et al. 1992) in the optical shell of NGC 2782 are higher than densities observed in the outflow region of many galaxies including M82, NGC 253, NGC 3079, NGC 3628, NGC 4527, NGC 4536, NGC 4666, NGC 7541, etc (e.g., see Lehnert & Heckman 1996). This suggests that the shell feature in NGC 2782 contains highly compressed ionised gas. The likely enhancement of the magnetic field strength in the compressed material could explain the strong RC emission in the shell.

Our results on the outflow morphology at  $\text{H}\alpha$ ,  $[\text{O III}]$ , and RC, together with the short outflow dynamical timescale ( $\sim 4 \times 10^6$  years) found from optical spectra by Boer et al. (1992), suggest that the outflow is dynamically young. This young dynamical phase could be attributed to several factors. The circumnuclear starburst in NGC 2782 may be younger than other starbursts which have a comparable luminosity, but a biconical freely-expanding outflow, e.g., M82. The dynamical timescale of the outflow in NGC 2782 is less than in M82, where we computed the timescale to be  $\sim 10^7$  years, using the size and expansion velocity of the optical nebula (e.g., Heckman et al. 1990). Furthermore, molecular gas is present around the circumnuclear starburst of NGC 2782 (see Fig. 3a, Plate L3) and it can remove energy from the outflow and slow down its expansion, for instance, by increasing the rate of radiative cooling (Heckman et al. 1993). In addition, the presence of clouds can reduce the density contrast between the dense compressed shell and the hot fluid it encloses, thereby delaying the onset of thermal instabilities which rupture the shell.

Knowledge of the distribution of hot ionised gas in the outflow would help assess its dynamical phase. In Fig. 4a, we give the  $\text{H}\alpha$  map of a larger region of NGC 2782, and in Fig. 4b, we compare this map with an archival ROSAT HRI X-ray map which has a resolution of  $\sim 12''$ . The X-ray map shows a bright core surrounded by fainter emission extending out to a

radius of  $20''$  (3.5 kpc). Unfortunately, the low resolution of the X-ray map does not resolve the outflow bubbles, and makes it difficult to separate hot gas driven out by the current outflow and that blown out by previous episodes of star formation. Such past episodes are not unlikely. The  $H\alpha$  image shows diffuse  $H\alpha$  arcs, loops, and filaments around the central region of star formation (Fig. 4a, Plate L4), and this morphology is highly suggestive of gas blown out in energetic episodes associated with previous starburst-driven outflows or with the interaction. The timescales involved also leave open the possibility of recurrent starbursts; the current outflow has a dynamical timescale of only  $\sim 4 \times 10^6$  years while the time of closest approach for the interaction is  $\sim 2 \times 10^8$  years (Smith 1994). Although the X-ray map has a low resolution, it nonetheless suggests an interesting possibility. The X-ray emission is more elongated to the north than to the south, and the northern RC bubble is also more extended and fragmented than the southern RC bubble (Fig. 3a, Plate L3); together, these facts suggest that the northern part of the outflow may have already broken out and allowed the hot gas to escape. It is unlikely that the more extended northern X-ray emission is an instrumental artifact because a similar extension is not seen in a point-like source near NGC 2782 in the ROSAT map. Furthermore, it is striking that the X-ray emission appears to extend out to the northwestern  $H\alpha$  arc whose narrow, bright appearance is suggestive of highly shocked gas (see Fig. 4b, Plate L4).

### 5. Cold, warm and hot gas in the outflow

Does the nuclear outflow in NGC 2782 contain cold molecular gas in addition to hot and warm ionised gas? Fig. 3a (Plate L3) shows two CO spurs (labelled O1 and O2) which are elongated along the kinematic minor axis, and appear to originate from the center of the CO bar where the starburst intensity peaks. The CO isovelocity contours show clear kinks at the base of these spurs, indicating deviations from circular motions (see Paper II). The spatial velocity plot (Fig. 5 of Paper II) shows non-circular motions of  $\sim 30 \text{ km s}^{-1}$  in the two CO spurs. With the near side of the disk being north, these velocities are consistent with vertical outflow of gas out of the galaxy plane and/or radial inflows of gas in the galaxy plane. The fact that the spurs are elongated along the minor axis and lie inside the RC outflow bubbles (Fig. 3a, Plate L3) strongly suggests that the spurs contain outflowing gas.

In order to determine the power needed to drive the outflow, we estimate the energy associated with the different phases of the ISM. With a Milky Way value for the CO- $H_2$

conversion factor, a radial vertical outflow velocity of  $(30 \text{ km s}^{-1}/\sin i)$ , an inclination  $i$  of 30 deg (see paper II), the CO spurs have  $\sim 2 \times 10^7 M_{\odot}$  of  $H_2$  and a kinetic energy of  $\sim 8 \times 10^{53}$  erg. The warm ionised gas in the optical nebula has a mass of  $\sim 1.2 \times 10^4 M_{\odot}$ , a kinetic energy of  $\sim 7 \times 10^{51}$  erg (Boer et al. 1992), and a thermal pressure of  $\sim 3 \times 10^{-9}$  dynes  $\text{cm}^{-2}$  for  $n_e \sim 600 \text{ cm}^{-3}$  (see § 4). Using the X-ray luminosity of  $5 \times 10^{40} \text{ erg s}^{-1}$  (from fluxes in Kinney et al. 1984 for a spectral index of 0) and following Nulsen, Stewart and Fabian (1984), we find that the hot gas has a total mass of  $\sim 6 \times 10^7 f^{0.5} M_{\odot}$ , a thermal energy of  $\sim 2 \times 10^{56} f^{0.5}$  erg, and a pressure of  $\sim 3 \times 10^{-10} f^{-0.5}$  dynes  $\text{cm}^{-2}$ . We assumed a temperature of  $3 \times 10^7 \text{ K}$ , a radius of  $15''$  (2.5 kpc) and a volume filling factor  $f$  for the hot gas. The above estimates suggest that cold molecular gas and hot ionised gas dominate the mass and energy in the outflow of NGC 2782. Although the outflows in M82 and NGC 2782 appear to be in different dynamical phases, they contain similar masses of cold, warm, and hot gas. In M82, these masses are estimated to be  $\sim$  a few  $\times 10^7 M_{\odot}$  (Stark & Carlson 1984),  $2 \times 10^5 M_{\odot}$  (Heckman et al. 1990) and  $1 \times 10^7 M_{\odot}$  (Schaaf et al. 1989) respectively.

The optical linewidths and line ratios in the central region of NGC 2782 do not indicate the presence of an AGN (see §3). Furthermore, NGC 2782 has a FIR luminosity ( $\sim 10^{44} \text{ erg s}^{-1}$ ) and warm FIR colors ( $S_{60\mu\text{m}}/S_{100\mu\text{m}} \sim 0.6$ ) similar to those of galaxies with the best evidence for supernova-driven winds (e.g., Lehnert & Heckman 1996). (It is however noteworthy that the ratios of FIR to blue optical luminosity of both NGC 2782 and NGC 3079 are below 1 rather than  $\geq 2$  as is the case in most of these galaxies.) We investigate if star formation alone can power the outflow. We assume that the total energy of  $\sim 2 \times 10^{56} f^{0.5}$  erg in the outflow is a fraction  $x$  of the total energy generated by supernovae, where  $x$  depends on how efficiently the kinetic energy of supernovae is thermalised. With a mean energy of  $\sim 2 \times 10^{51}$  erg per supernova (Mac Low & McCray 1988) and an outflow timescale of  $4 \times 10^6$  yrs (Boer et al. 1992), the average supernova rate needed to power the outflow is  $\approx (10^{-2} f^{0.5}/x) \text{ yr}^{-1}$ . Using the FIR luminosity of  $2 \times 10^{10} L_{\odot}$  as an estimate for the bolometric luminosity, and applying the starburst model of Rieke et al. (1980) gives a supernovae rate of  $\approx 0.1 \text{ yr}^{-1}$ . For a volume filling factor  $f$  of 0.1, the supernovae rate from the starburst can power the outflow if  $x \geq 5\%$ . Stellar winds can also be an important energy source in establishing a wind (Leitherer & Heckman 1995).

NGC 2782 provides an unparalleled opportunity for setting observational constraints on the

poorly-studied, early evolutionary phase of a starburst-driven outflow. Further observations of the dynamically young outflow in NGC 2782 can extend the study presented in this paper. In particular, future high resolution X-ray and near-infrared observations will help to further constrain the dynamical phases of both the southern and northern outflows (§ 4), better estimate the poorly-known quantities  $f$  and  $x$ , and study how the properties of the circumnuclear starburst influence the outflow it is driving.

## 6. Acknowledgements

This work has been partially supported by an AAUWEF Fellowship, a Grant-in-Aid of Research from Sigma Xi (The Scientific Research Society), an Amelia Earhart Fellowship, and an NSF grant AST-9322779. We thank D. J. Saikia and A. Pedlar for the 5 GHz RC maps, J. Barnes at NOAO for the production of solitaires, and the High Energy Astrophysics Science Archive Research Center, provided by NASA’s Goddard Space Flight Center, for the ROSAT X-ray map. We thank Richard Larson and referee Matthew Lehnert for helpful comments.

## REFERENCES

- Arp, H. C. 1966, *Atlas of Peculiar Galaxies* (Caltech Institute of Technology, Pasadena)
- Balzano, V. A. 1983, *ApJ*, 268, 602
- Baum, S. A., O’Dea, C. P., Dallacassa, D., de Bruyn, A. G., & Pedlar, A. 1993, *ApJ*, 419, 553
- Bland, J., & Tully, B. R. 1988, *Nature*, 334, 43
- Boer, B., Schulz, H., & Keel, W. C. 1992, *A&A*, 260, 67
- Chevalier, R. A., & Clegg, W. 1985, *Nature*, 317, 44
- Colbert, E. J. M., Baum, S. A., Gallimore, J. F., O’Dea, C. P., & Christensen, J. A. 1996, *ApJ*, 467, 551
- Dahlem, M. et al. 1997, *A&A*, 320, 731
- Dekel, A., & Silk, J. 1986, *ApJ* 303, 39
- Devereux, N. A. 1989, *ApJ*, 346, 126
- Evans, I. N., Koratkar, A. P., Storchi-Bergmann, T., Kirkpatrick, H., Heckman, T. M., & Wilson, S. A. 1996, *ApJS* 185, 93
- Fabbiano, G., Kim, D-W, & Trinchieri, G. 1992, *ApJS* 80, 531
- Ford, H. C., Dahari, O., Jacoby, G. H., Crane, P. C., & Ciardullo, R. 1986, *ApJ*, 311, L7
- Heckman, T. M., Armus, L., & Miley, G. K. 1990, *ApJS*, 574, 833
- Heckman, T. M., Lehnert, M. D., & Armus, L. 1993, in “The Environment and Evolution of Galaxies”, eds. J. M. Shull and H. A. Thronson, Jr, p. 455
- Hodge, P. W., & Kennicutt, R. C. 1983, *ApJ*, 268, L75
- Hunter, D. P., Gillett, F. C., Gallagher, J. S., Rice, W. L., & Low, F. J. 1986, *ApJ*, 303, 171
- Irwin, J. A., & Seaquist, E. R. 1988, *ApJ*, 335, 658
- Ishizuki, S. 1994, ‘Astronomy with Millimeter and Submillimeter Wave Interferometry’, *IAU Coll.* 140, ed. Ishugiro, M., & Welch, J. M., 292
- Jogee, S., Kenney, J. D. P. , & Smith, B. J. 1997, *ApJ*, submitted. (Paper II)
- Kennicutt, R. C., Jr. 1983, *ApJ*, 272,54

- Kennicutt, R. C., Jr., Keel, W. C., & Blaha, C. A. 1989, *AJ*, 97, 1022
- Kinney, A. L., Bregman, J. N., Huggins, P. T.,  
Glassgold, A. E., & Cohen, R. D. 1984, *PASP*, 96, 398
- Lehnert, M. D., & Heckman, T. M. 1995, *ApJS*, 97, 89
- Lehnert, M. D., & Heckman, T. M. 1996, *ApJ*, 462, 651
- Leitherer, C., & Heckman, T. M. 1995, *ApJS*, 96, 9
- Mac Low, M., & McCray, R. 1988, *ApJ*, 324, 776
- Mihalas, D., & Binney, J. 1981 in “Galactic Astronomy”, p. 339.
- Nulsen, P. E. J., Stewart, G. C., & Fabian, A. C. 1984, *MNRAS*, 208, 185.
- Puxley, P. J., Hawarden, T. G., & Mountain, C. M. 1990, *ApJ*, 364, 77.
- Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., Tokunaga, A. T. 1980, *ApJ*, 238, 24
- Sandage, A. & Bedke, J., *The Carnegie Atlas of Galaxies*, 1994
- Saikia, D. J., Pedlar, A., Unger, S. W., & Axon, D. J. 1994, *MNRAS*, 270, 46
- Sakka, K., Oka, S., & Wakamatsu, K. 1973, *PASJ*, 25, 153
- Schaaf, R., Pietsch, P. L., Biermann, P. L., Kronberg, P. P., & Schmoltzer, T. 1989, *ApJ* 336, 762
- Scoville, N. Z., Carlstrom, J. E., Cahndler, C. J., Phillips, J. A., Scott, S. L., Tilanus, R. P. J., & Wang, Z. 1993, *PASP*, 105, 1982
- Seaquist, E., & Odegard, N. 1991, *ApJ*, 369, 320.
- Smith, B. J. 1991, *ApJ*, 378, 39
- Smith, B. J. 1994, *AJ*, 107, 1695
- Soifer, B. T., Houck, J. R., & Neugebauer, G. 1987, *Ann. Rev. Astr. Ap.*, 25, 1987
- Stark, A. A., & Carlson, E. R. 1984, *ApJ*, 279, 122
- Tomisaka, K., & Ikeuchi, S. 1988, *ApJ*, 330, 695
- Veilleux, S., Cecil, G., Bland-Hawthorn, J., Tully, R. B., Filippenko, A. V., & Sargent, W. L. W. 1994, *ApJ*, 433, 48

Young, J. S., Xie, S., Tacconi, L., Knezek, P., Viscuso, P., et al. 1995, ApJS, 98, 219

**Fig. 1 (Plate L1)**— The WIYN R image of NGC 2782 with a  $6.5'$  (66 kpc) field of view reveals the optical disk bracketed by two stellar tails. Except for three ripples at radii of  $25''$ ,  $45''$ , and  $60''$ , the optical disk is relatively undisturbed within a radius of  $\sim 1'$  (10 kpc).

**Fig. 2 (Plate L2)**— (a) The WIYN B-V image with a  $1.6'$  (16.3 kpc) field of view shows two dust lanes which are offset from the nucleus and extend out to the inner ripple at  $r \sim 25''$  (4.2 kpc). Lighter regions in the image have redder B-V colors and darker regions have bluer B-V colors. The northern dust lane is redder and more prominent than the southern one. The dust lanes bracket the inner few kpc region which harbors one of the most luminous starbursts among nearby ( $D < 40$  Mpc) spirals. (b) The  $0.8''$  resolution WIYN  $H\alpha$  image with a central  $20''$  (3.4 kpc) field of view, shows a central  $H\alpha$  peak, an arc of star formation extending east-west, and a southern  $H\alpha$  outflow which has a well-defined bubble morphology with a shell feature at its edge.

**Fig. 3 (Plate L3)**— **The starburst driven outflow:** (a) 5 GHz RC (contours, Saikia et al. 1994) on the  $2.1'' \times 1.5''$  CO map (greyscale, from Paper II) for the central  $20''$  (3.4 kpc). It is likely that the main RC peak, as well as the secondary eastern and western peaks, are due to massive star formation. In contrast, the northern and southern RC bubbles which are elongated along the kinematic minor axis, are associated with little molecular gas and are probably part of the starburst-driven outflow. The two CO spurs, labelled O1 and O2, are also elongated along the kinematic minor axis and lie inside the RC outflow bubbles. The contour levels are 5, 10, 30, 50, 70, 90, 100 % of the peak flux (3.97 mJy per beam). (b) The  $0.8''$  resolution WIYN  $H\alpha$  image shows a region of star formation whose activity peaks between the two CO lobes, and a remarkable southern  $H\alpha$  outflow bubble with an outer shell feature at  $\sim 6''$  south. The cross marks the 5 GHz RC peak. The contour levels are 65, 75, 85, 90, 95, 100 % of the peak flux. (c)  $H\alpha$  (contours) on the the 5 GHz RC (greyscale). The  $H\alpha$  and RC peak are coincident within the uncertainties, and lie between the two CO lobes. The  $H\alpha$  shell at  $\sim 6''$  (1 kpc) south coincides with the shell in the southern RC bubble. (d) The [O III] image (with  $1.3''$  seeing) has a similar bubble morphology as the outflowing  $H\alpha$ , and shows a strong extranuclear peak at  $\sim 6''$  south. This extranuclear peak occurs in the region where long-slit spectra shows a maximum in the intensity and FWHM of blueshifted [O III] lines.

**Fig. 4 (Plate L4)** — (a) The  $H\alpha$  image with a  $76''$  (13 kpc) field of view. This figure shows a string of HII regions which coincides with the first optical ripple at  $r \sim 25''$  (4.2 kpc), a bright

northwestern  $H\alpha$  arc, and diffuse  $H\alpha$  loops and filaments which surround the central starburst region. (b) The ROSAT X-ray map (contour) of resolution  $\sim 12''$  on the  $H\alpha$  image (greyscale). There is bright emission in the central  $8''$  (1.4 kpc) radius where the optical and RC outflow bubbles lie, and fainter emission which extends further out. The faint X-ray emission is more extended northwest than southeast, and it stretches out to the prominent northwestern  $H\alpha$  arc.

This figure "p1fig1.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9707069v2>

This figure "p1fig2a.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9707069v2>

This figure "p1fig2b.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9707069v2>

This figure "p1fig3a-d.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9707069v2>

This figure "p1fig4a.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9707069v2>

This figure "p1fig4b.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9707069v2>